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Pushover analysis of the district office building damaged during 2016 Meinong, Taiwan earthquake

P.W. Weng & Y.A. Li
National Center for Research on Earthquake Engineering, Taiwan.

S.J. Hwang
National Taiwan University, Taiwan.

J.W. Lai
Degenkolb Engineers, U.S.A.

ABSTRACT

After the 2016 Meinong Earthquake in Taiwan, the National Center for Research on Earthquake Engineering (NCREE) and Degenkolb Engineers formed a reconnaissance team to survey the earthquake-damaged buildings. The reconnaissance team visited three district office buildings that were designed and constructed based on similar construction documents. These three buildings had different levels of damages after the earthquake. Both NCREE and Degenkolb Engineers analyzed three district office buildings, where NCREE used the Taiwan Earthquake Assessment for Structures by Pushover Analysis (TEASPA) method, while Degenkolb Engineers analyzed the buildings following the ASCE 41-13 Nonlinear Static Procedure. This paper presents the seismic evaluation results of one district office building from different simulation models. The concept of seismic evaluation methodologies and the effects of simulation assumptions in structural members such as columns, partial height walls, and partition walls are compared. The comparison of evaluation results with observed building damages is also discussed.

1 INTRODUCTION

Taiwan is located on the border between the Eurasian Plate and Philippine Sea Plate. Because of the effect of plate motion, there are many faults are formed at the western part of Taiwan. The shake by movement on faults is one of the reasons that caused the earthquake. There are probably sixty percent buildings are close to the faults less than 10 km, and therefore the seismic performance evaluation of building is an important research topic in Taiwan.

For seismic evaluation of existing buildings, US practicing engineers usually adopt ASCE/SEI 41-13 (ASCE 2014) standard. However, the practicing engineers in Taiwan are typically familiar with the NCREE nonlinear static pushover analysis method to evaluate the building seismic performance. This paper presents the seismic evaluation results of one district office building from different simulation models. The concept of seismic evaluation methodologies and the effects of simulation assumptions in structural members such as columns, partial height walls below windowsills, and partition walls are compared. The comparison of evaluation results with observed building damages is also briefly discussed.

2 DISTRICT OFFICE BUILDING

2.1 Disaster Reconnaissance of 2016 Meinong Earthquake

According to the earthquake report of the Central Weather Bureau (CWB 2016), the Meinong Earthquake struck at 03:57:26.1 on Tuesday, February 6th, 2016. The epicenter was at 22.92° N latitude, 120.54° E longitude, 27.1 km north-north-east of Pingtung County, near the town of Meinong, Kaohsiung. The tremor measured 6.6 on the Richter scale, and the focal depth was 14.6 km (Fig. 1).

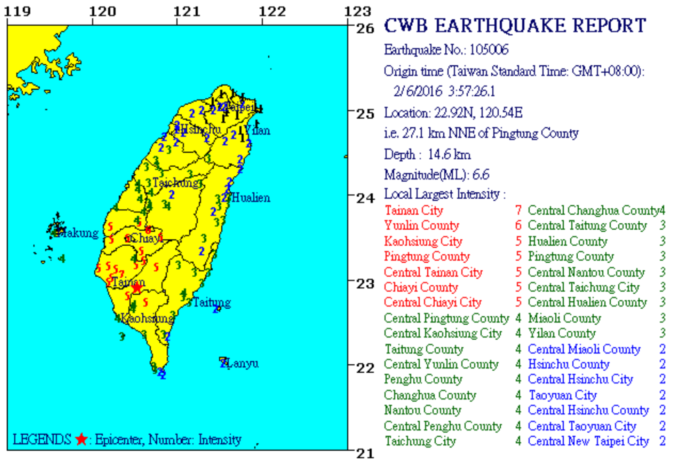

Figure 1: The 2016 Meinong Earthquake report (CWB 2016) by the Central Weather Bureau, Taiwan.

In order to understand the damages of buildings caused by the earthquake, NCREE and Degenkolb Engineers formed a joint reconnaissance team to survey the earthquake-damaged buildings in the Tainan area and to collect structural characteristics of those buildings. The reconnaissance investigations showed that the district office buildings were similar in use, had similar structural characteristics, and had similar level of damages during Meinong earthquake. One of those damaged district offices is evaluated in this study, and the building information is briefly described below.

2.2 Juojhen District Office

Juojhen district office is located at the northwest direction of the epicenter with epicentral distance of 20 km. The longitude and latitude coordinates are 120.41° East and 23.06° North. The Juojhen district office building is a three-story reinforced concrete structure. The first and second stories were built in 1974 primarily as a district office, and the third story addition was built in 1984 as a civic center. Backside addition was built at the same time in 1984 as additional staff offices. The building footprint dimension is 33 meters long and 17.5 meters wide. The first floor has an area of about 559 square meters. Because of the first floor is for administrative use, it is lack of partition walls and has many short columns right next to the windowsills and partial height walls. The soft-story problem is causing damage concentration at the first story and poor building performance during the earthquake. Figure 2 shows the building first floor plan and the locations of damaged columns. Most of the damaged columns (Line 1) were shear failure caused by short column effect.

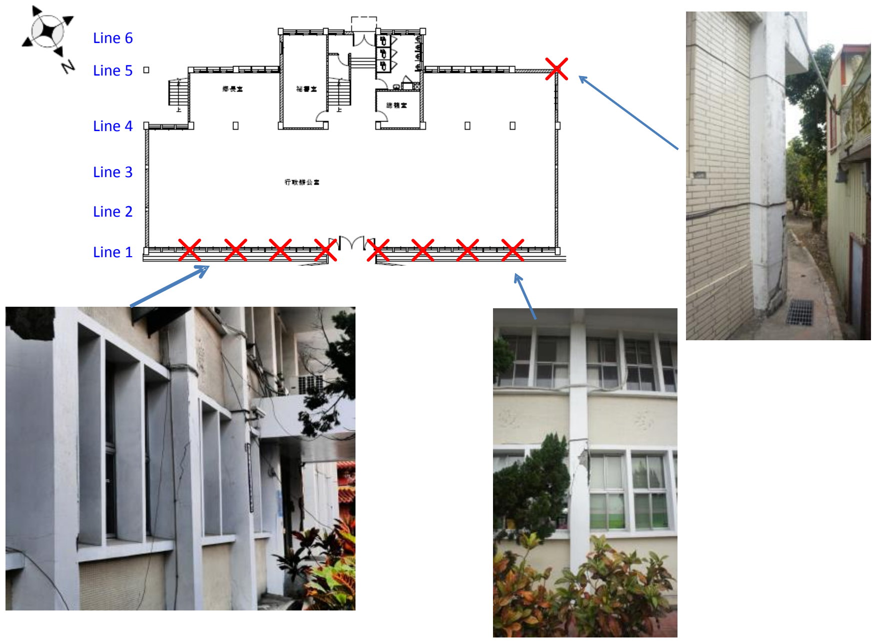

Figure 2: The damages of Juojhen district office.

3 SEISMIC ASSESSMENT OF DISTRICT OFFICE BUILDING

3.1 Seismic assessment results from TEASPA method by NCREE and from ASCE 41-13 method by Degenkolb Engineers

Both Degenkolb Engineers and NCREE analyzed the Juojhen district office building (Lai et. al 2018, Weng et. al 2018), where NCREE used the Taiwan Earthquake Assessment for Structures by Pushover Analysis (TEASPA) method, while Degenkolb Engineers analyzed the buildings following the ASCE 41-13 Nonlinear Static Procedure. Detail descriptions of TEASPA method can be found in literatures published by Hsiao et al (Hsiao et. al 2013 & Hsiao et. al 2015).

Figure 3 shows the force-displacement curves (pushover curves) from two different ETABS (CSI 2008 & 2017) models developed following different modeling assumptions. We can clearly see that the force-displacement curve from NCREE's evaluation model (Analysis 1) and the force-displacement curve from Degenkolb Engineers' evaluation model (Analysis 2) are very different. Visible evidence can be found in the curve from Analysis 1 is the stiffness softening effect. The increase of lateral force slows down after the shear failure occurs in columns. After reaching the peak capacity of the structure, the lateral force decreases until the end of analysis. While the force-displacement curve from Analysis 2, the stiffness softening effect is not that obvious, and the analysis stops due to convergence issue before the peak base shear capacity of the structure is reached.

From the reconnaissance investigation, it was found that the Juojhen district office building had severe damage during the earthquake. The force-displacement curve of Analysis 2 seems not reasonable in the global sense. However, it should be noted that in ASCE 41-13 procedure, the evaluation is performed to check every single component, not just the global behavior. In order to understand the effects of modeling assumptions in structural members to building global behavior, the modeling assumptions for columns, partial height walls below windowsills, and partition walls in NCREE's model are investigated, and the analysis results are discussed in the following sections.

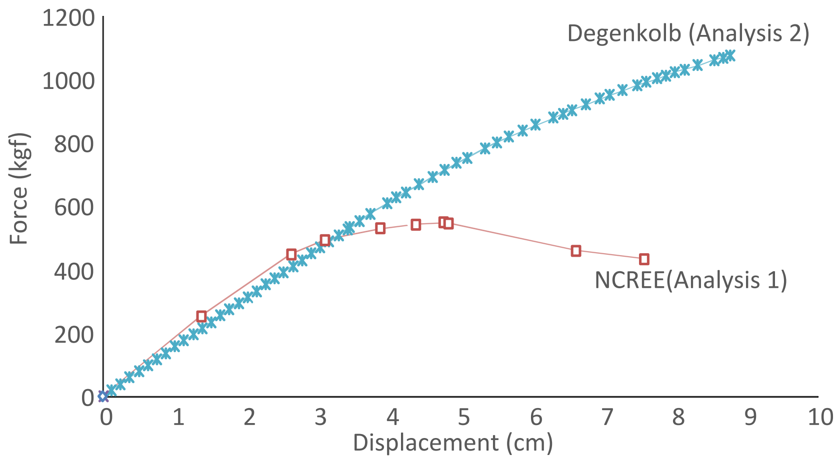

Figure 3: Comparison of the force-displacement curves from ETABS models developed by Degenkolb Engineer and NCREE.

3.2 The effect of nonlinear hinges in columns

One of the main differences between two ETABS models developed by NCREE and Degenkolb is the nonlinear hinges assigned in column elements. Base on the TEASPA method, it recommends using flexural hinges at top and bottom of columns, and a shear hinge at the middle of the column. Figure 4 shows the plastic hinge distributions along frame Line 1 of NCREE's model when the maximum base shear is reached. We can find most of the first-floor columns fail in shear. Compared with the observations during the reconnaissance, the TEASPA evaluation results match actual damage and well predict the failure mode of the structural member.

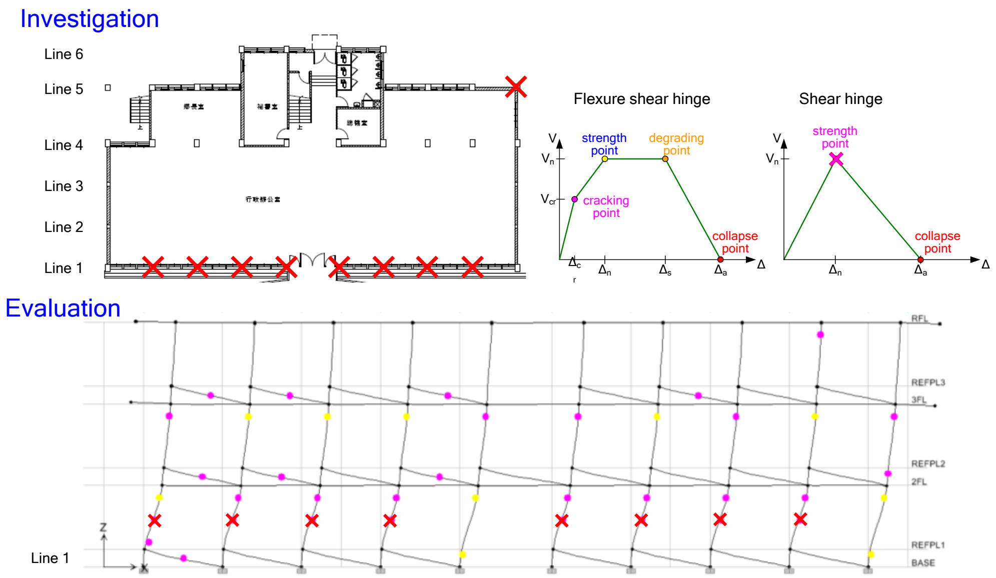

Figure 4: Comparison between actual damages and TEASPA evaluation results.

The ETABS model developed by Degenkolb per ASCE 41 standard only assigned flexural hinges at top and bottom of columns. Capacity of the flexural hinges and the hinge backbone curves are adjusted according to the limit state analysis depending on the controlling conditions per ASCE 41-13 (i.e. condition (i) to (iv)). Here we remove the shear hinges in columns from NCREE's evaluation model and call it the Analysis 1-1 to investigate the effect on pushover curve. Figure 5 shows the plastic hinge distribution of Analysis 1-1 model when the maximum base shear is reached. Without shear hinges in columns, we can find the columns in the first-floor changed to flexural failure as expected.

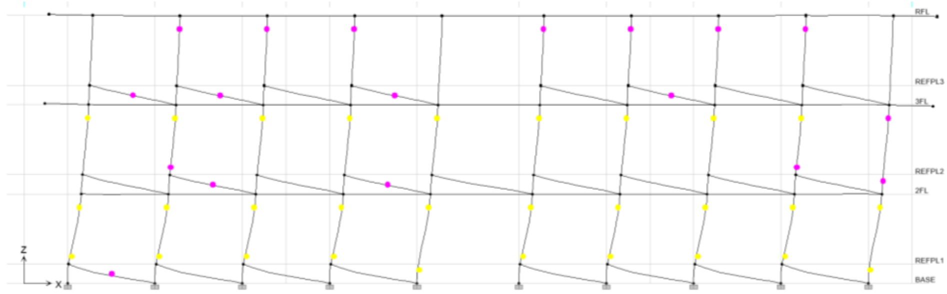

Figure 5: Plastic hinge distribution of Analysis 1-1 model.

Compared with the Analysis 1 pushover curve, the force-displacement curve of Analysis 1-1 is similar, and the peak base shear is higher (see Fig. 6). The stiffness softening effect is also obvious from the curve. After the maximum strength is reached, the drop of lateral force is slower than Analysis 1. Figure 7 shows the peak column base shear forces of different models. It can be found that the peak column base shear force in Analysis 1 (Fig. 7a) is changing from 549 tf to 591 tf (Analysis 1-1, see Fig. 7b). The main reason that causes the increase of peak base shear force is the change of column failure mode. After the removal of shear hinges in columns (without adjusting the flexural hinge capacities), the shear capacities of the columns are determined from the flexural strengths instead of the shear strengths directly from the shear hinges. Hence, the shear capacities of columns are increased due to the higher flexural strengths.

3.3 The effect of partial height walls below the windowsills

In order to have better ventilation and natural light, the district office buildings often have a lot of windows. The partial height walls under the windows will restrain the columns and reduce the clear height of the columns. According to the reconnaissance investigations, we often found the damage to district office buildings was due to the shear failure of the columns next the partial height walls (see Fig. 2). Therefore, the effect of the partial height walls cannot be neglected during seismic evaluation.

In NCREE's evaluation model, the brace members were used to simulate the nonlinear behavior of the masonry partial height walls. The compression struts with nonlinear axial hinges were used to simulate the partial height walls. Different from the NCREE's evaluation model, the Degenkolb Engineers' evaluation model simply used elastic shell elements to simulate the partial height walls. Here we further change the Analysis 1-1 model, using the elastic shell elements instead of the brace members (called Analysis 1-2 model) and conduct the pushover analysis. As shown in Figure 6, the base shear capacity of Analysis 1-2 model increases substantially, and the stiffness softening effect is not significant.

The base shear force of Analysis 1-2 model further increased to 797 tf as shown in figure 7c. The shell element can be subjected to both tension and compression force in the model. Additionally, the use of elastic shell elements in the evaluation model is overestimating the capacity of the partial height walls.

3.4 The effect of partition walls

Another difference between two models developed by NCREE and Degenkolb is the inclusion of partition walls in the transverse direction. The partition walls are not included in NCREE's evaluation model. In order to understand the effect of the partition walls, here we added the shell element walls to the evaluation model (called model Analysis 1-3). From the force-displacement curve of Analysis 1-3 model (see Fig. 6), the post-yield stiffness of the structure is higher than that of the Analysis 1-2 model, and the analysis stops at the ascending region of the pushover curve. The force-displacement curve of the Analysis 1-3 is quite similar to the curve of the Analysis 2. And the peak base shear before termination of analysis further increases to 903 tf as shown in Fig. 7d. The shell element partition walls in Analysis 1-3 model provides additional load paths (through wall out-of-plane behavior), which increases the strength of the overall structure in the pushover direction.

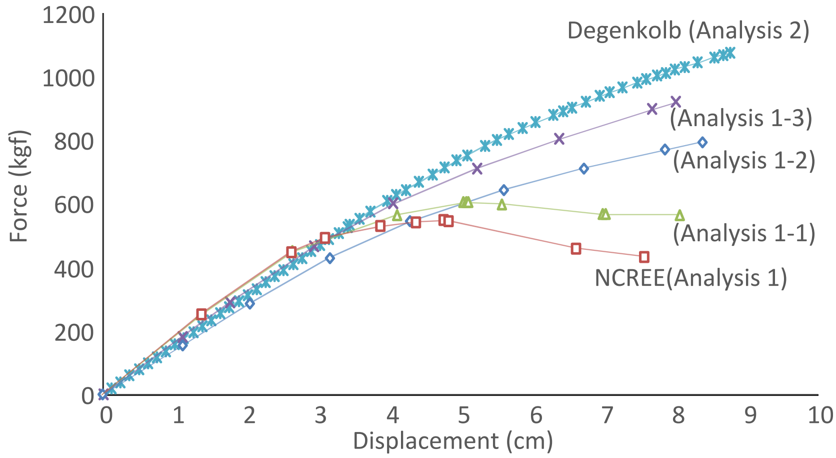

Figure 6: Comparison of the force-displacement curve.

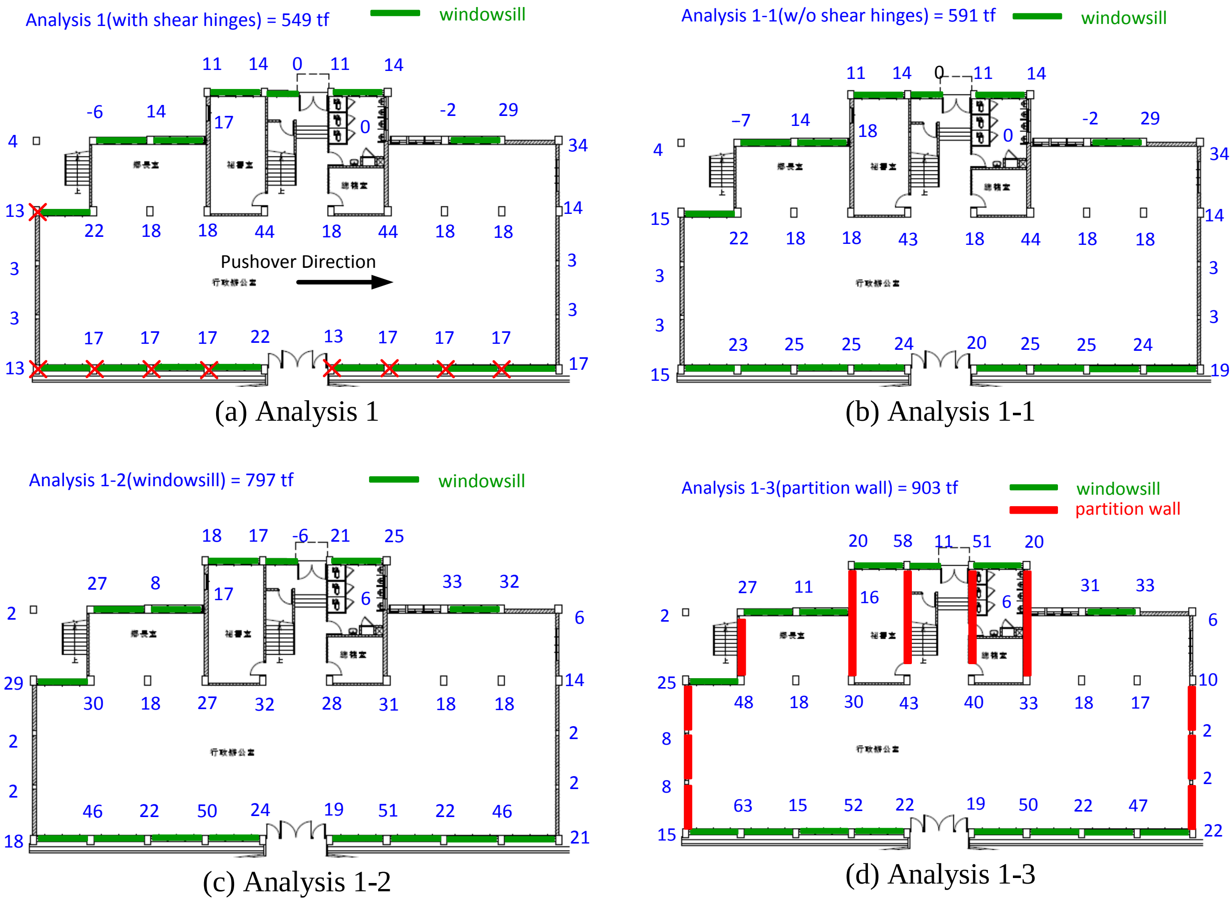

Figure 7: Comparison of the base shear forces in different models.

4 CONCLUSION

Although not all of different modeling assumptions between TEASPA and ASCE 41 procedures are addressed and discussed here, the evolution of analytical models from model Analysis 1-1 to Analysis 1-3 illustrates the effects of hinge types (i.e. shapes of nonlinear hinge backbone curves), partial height walls and partition walls. Based on the study shown in this paper, some conclusions and suggestions are summarized as follows:

1. Base on the comparison between the observed earthquake damages and the evaluation results, the TEASPA method can well predict the failure mode of structural members.
2. The removal of shear hinges in the columns does affect the peak base shear capacity of the structure, but the effect is less significant than the effect from the partial height wall modeling assumption in this case.
3. The use of elastic shell elements to simulate the partial height walls below the windowsills has significant effect on the global pushover curves which may overestimate the base shear capacity.
4. The contribution from the partition walls also plays an important role and particularly the wall out-of-plane behavior in this case.

5 ACKNOWLEDGMENTS

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